into the link budget for the base stations, and $E_b/N_0 > x_0$ at the nominal end-of-range, then it could be claimed that T_b could be reduced as the inverse-square of the bandwidth while maintaining σ_t constant at the coverage perimeter. However, doing so simply reduces E_b/N_0 at the perimeter, reducing the margin. The additional capacity is being gained at the expense not only of bandwidth, but also of signal strength margin, which presumably was designed into the system for good reason. Indeed, capacity can also be increased by simply decreasing T_b (and reducing the margin) without increasing the bandwidth, although σ_t at the coverage perimeter will increase.

If the main signal impairment is an interference source of received power I, it could be argued from (14) that the effective noise spectral density is $N_0 = I/B$, so N_0 and hence T_0 decreases with bandwidth. While this is true for a single interference source, there will be numerous interfering Part 15 transmitters, randomly distributed in space and frequency. The greater the receive bandwidth of the AVM system, the greater the number of interference sources per unit area that will fall within the bandwidth. Moreover, as will be seen in the next section, the interference power that can be received from even a single Part 15 device is so high that bandwidth expansion is not a practical means to mitigate it (the impracticality of using bandwidth expansion to overcome the effect of a strong interfering signal is also discussed in Appendix 1 to Teletrac's Comments, pp. 37-38).

4. PROPAGATION AND RECEIVED SIGNAL POWER

4.1 Desired Signal Power

In the mobile radio environment, there often is no line-of-sight path between a vehicle and a base station several miles away, and the signal propagates via reflection, diffraction, and penetration through obstructions. The received signal often is modeled as having a median that varies as $d^{-\gamma}$, where d is the base-to-mobile distance and γ is the path loss exponent. Random large-scale variations due to "shadow fading" and small-scale variations due to multipath[12] are superimposed on the variations in the median due to changes in d.

Models such as that of Hata [10], which is based on data gathered by Okumura [11], predict the median path loss as a function of d given the frequency, antenna elevations, and type of environment (i.e., urban, suburban, rural). Using the Hata model, the median received power (in dBm) can be expressed in the form

12. The terms "large-scale" and "small-scale" refer not to the magnitude of the signal strength variations associated with these phenomena, but rather to the distances over which the variations occur. In a severe multipath environment, variations due to multipath are quasi-periodic with minima a half-wavelength apart, on average. Conversely, the variations due to shadow fading occur over many wavelengths (typically tens or hundreds of feet).

$$C = P_{TX} - \alpha - 10\gamma \log d + g_B \,, \tag{17}$$

where P_{TX} is the ERP of the mobile in dBm, g_B is the gain of the base antenna in dB, and α and γ are given by the Hata model; α depends on frequency, antenna elevations, and environment, and γ depends on the antenna elevations.

The following table shows α and γ for various base antenna elevations in the "suburban" environment at 915 MHz, and the median received power for $d = 5$ miles, assuming a half-wave dipole on the base (2.15 dB gain), and a transmit power (from the vehicle) of 1 watt ERP. For an urban area, the median received power levels would be 10 dB lower at this frequency.

h_B(ft)	α (dB)	γ	C, dBm ($d = 5$ mi)
50	128.3	3.72	-122.1
100	123.7	3.52	-116.2
200	119.2	3.32	-110.2
300	116.5	3.21	-106.7
400	114.6	3.12	-104.3
500	113.1	3.06	-102.4

These levels represent the median signal strength that a Teletrac base station would expect to receive from a mobile 5 miles away. As can be seen, the median received signal is on the order of -100 to -120 dBm, depending on the base antenna elevation. The median received signal level varies roughly 9 to 11 dB per octave with d. For example, with $h_B = 200$ ft, halving d to 2.5 miles would increase C by roughly 10 dB, to about -100 dBm.[13]

Assuming the system is engineered for a noise floor of -90 dBm (see p. 9 of Appendix 1 to Teletrac's Comments), then a -25 dB carrier-to-noise threshold would allow the system to operate with a received signal strength of -115 dBm, which gives a range of about 5 to 10 miles, depending on the tower height. In reality, some margin must be allowed for fading effects, but that will be ignored here in the interests of simplicity.

4.2 Interference Power From Part 15 Devices

The path loss between a Part 15 device at street level and several miles from a Teletrac base station can be modeled using Hata's formulas. However, the Hata model does not apply for separations less that 1 km, and microcell propagation models must be considered. Such

13. The variation of C with d is 3γ dB per octave; that is, if d doubles, C decreases by 3γ dB.

models are discussed by Green [12] and by Green and Hata [13], who observe that in some cases (such as on a roadway when a line-of-sight path is present) the "two-path" model gives reasonably accurate results. This model assumes a direct ray and a ground-reflected ray, with the total received field being the complex phasor sum of the two. The reflected ray thus can positively or negatively reinforce the direct ray, depending on the phase relationship between the two. The ground-reflection coefficient can be calculated as a function of the incidence angle, as discussed by Jordan and Balmain [14].

Fig. 6 shows the received power vs. d for h_B = 100 ft, f = 915 MHz, and P_{TX} = 1 watt (the maximum transmitted power for a Part 15 device operating in the 902-928 MHz band under §15.247 of the FCC Rules). The parameters σ and ϵ_r are the conductivity (mhos/meter) and relative dielectric constant assumed for the ground. As can be seen, the reflection causes oscillations of 5 to 10 dB about the free-space (d^{-2}) level, until the "break point" (roughly a mile here) is reached and the received signal begins to drop off as d^{-4}. For distances up to a mile, the received interference power lies between -30 dBm and -60 dBm. Figs. 7 and 8 show similar curves for 200 ft and 400 ft base station antenna heights, respectively. Fig. 9 shows the received signals for all three heights together.

The levels of interference shown by these curves will create a serious problem for receivers such as Teletrac's. To illustrate, assume that receiver coverage boundaries are designed for a noise floor of -90 dBm (i.e., a received signal power of about -115 dBm). A received interference level of -55 dBm, which corresponds to an interference source roughly 4000 feet from the base for a two-path model with h_B = 100 ft, would require an increase of 35 dB in the desired signal level, which would decrease the range by roughly a factor of 10, and the coverage area by a factor of 100. This effectively would remove the base station from service.

Finally, it is reasonable to assume that because of the interference-prone, uncontrolled nature of the 902-928 MHz band, many Part 15 devices will be designed with some degree of frequency agility, to allow them to avoid interference so as to provide their customers with clear communication channels. Unfortunately, such capability will not be of much help in reducing their interference to a system such as Teletrac's, because it depends on the ability to detect an interfering signal. The reverse-link signal in Teletrac's system will emanate from a vehicle near the ground, will be spread over a wide bandwidth, and will be of very short duration. Hence, it is unlikely that it will be seen by the Part 15 device, which will have no way of knowing that the band is "in use," and will therefore have no reason to avoid transmitting in it.

4.3 Effect of Frequency Hopping and Direct Sequence Modulation of the Part 15 Signal

Section 15.247 of the FCC Rules allows Part 15 devices operating in the 902-928 MHz band to use up to 1 watt of RF transmit power providing either direct sequence modulation or frequency hopping is used. The purpose of this subsection is to discuss the effect of these requirements on the potential for interference to Teletrac's receivers.

Direct sequence modulation spreads the transmitted signal power over a bandwidth much greater than the information bandwidth. Section 15.247 requires a "spread" bandwidth of at least 500 kHz and a processing gain of at least 10 dB, which means that the spread bandwidth must be roughly ten times the information bandwidth, or more. The spectrum-spreading can reduce the interference caused by the Part 15 device if the "spread" Part 15 signal has a bandwidth greater than that of the victim receiver, which will "see" only a fraction of the power from the Part 15 device. For a wideband receiver such as Teletrac's, however, it will not have much impact on the interference potential in many cases. Consider, for example, a system with an information bandwidth of 100 kHz and a spread bandwidth of 1 MHz. Depending on channel alignment, the entire spectrum of the Part 15 transmitter can fall within the receive bandwidth of the Teletrac receiver. Further, several such Part 15 devices can fall within the Teletrac receiver's passband without interfering with each other. Hence, unless it spreads its signal over a very wide band, a Part 15 device using direct sequence modulation poses essentially the same interference threat to the Teletrac system as it would using conventional narrowband modulation.

The frequency hopping requirements in §15.247 require that a device operating in the 902-928 MHz band use a hop sequence consisting of at least 50 randomly-selected frequencies, and transmit on each frequency no longer than 400 milliseconds at a time. This means that on the average, a single frequency hopper will be operating within a given 8 MHz bandwidth roughly 30% of the time. If there are k frequency hoppers operating near a Teletrac receiver, the probability that at least one of them is within a given 8 MHz bandwidth at any given time is $1-0.7^k$, assuming their hop sequences are random and mutually independent. Thus, if there are 2 hoppers, the probability that a given 8 MHz band is "clear" is 49%; for 3 hoppers it is 34%, and for 4 hoppers it is 24%. It should also be noted that this problem will not tend to be alleviated to any great extent by interference among the hoppers themselves. First, several hoppers may have good propagation paths to the Teletrac receiver due to its high elevation, but poor paths to each other, if they are near the ground. They therefore may cause no discernible interference to each other. Second, due to the wide bandwidth of the Teletrac receiver, a number hoppers with relatively narrow channel bandwidths (e.g., 100-200 kHz) can operate within the same Teletrac receiver bandwidth simultaneously without causing cochannel interference to each other, even if they are operating in close proximity.

It appears, therefore, that the spread spectrum requirement in §15.247 associated with the allowed 1-watt transmit power will not significantly mitigate the interference threat posed by Part 15 devices to receivers of systems such as Teletrac's. Further, the wider the bandwidth of the AVM receivers, the more severe the problem.

5. CONCLUSIONS

This discussion has focussed on the receiver in a Teletrac base station, the function of which is to estimate the time-of-arrival (TOA) of a signal pulse received from the vehicular transmitter. Of interest is the relationship between the TOA estimation error and the interference sustained by the base receiver. The performance of the Teletrac receiver (as given in Teletrac's Comments [2] was reviewed and compared to the Cramer-Rao bound, which gives a lower limit on the rms TOA estimation error as a function of the RF carrier-to-noise ratio (CNR). In both cases, the rms TOA estimation error varies inversely with the square root of the CNR, and the Teletrac receiver's performance is within about 5-6 dB of the Cramer-Rao bound. However, the inverse-square-root relationship only applies when the CNR is above the receiver's threshold, which for the current version of the Teletrac receiver, appears to be about -25 dB. When the CNR drops below this level, the rms TOA estimation error seems to vary roughly as the inverse-square of the CNR. This threshold effect has not been taken into account in the arguments of bandwidth-versus-capacity tradeoffs made by Teletrac. Taking into account the threshold effect, it appears that the claimed "bandwidth squared" capacity gain is illusory, as explained in section 3. In fact, the maximum capacity of a system will increase only as the square root of the bandwidth, given a maximum allowable rms TOA estimation error. Hence, the argument that more bandwidth is needed to support larger capacities does not appear valid.

Section 4 provided calculations of desired and interfering signal power as seen by a Teletrac receive base station, and it was shown that a Part 15 device with a line-of-sight path to a base station (which may not be unusual, considering that the base stations are typically elevated several hundred feet above the terrain, to maximize coverage) can deliver interference power levels of -30 to -60 dBm into the receiver, which will essentially render the receiver useless. This analysis considered only a single interference source, but as the penetration of Part 15 devices grows, it may not be uncommon for several such devices to fall within the wide Teletrac reverse channel passband simultaneously. Clearly, the wider the Teletrac reverse channel bandwidth, the greater the vulnerability to uncontrolled interference.

Based on the results given here, it is concluded that Part 15 devices in the 902-928 MHz band constitute a serious interference threat to systems such as Teletrac's that depend on reception of relatively weak signals. The question of how often interference incidents will occur is beyond the scope of this paper, because that depends on the penetration achieved by Part 15 devices. However, the increase in that penetration during the next 3-5 years is expected to be considerable, especially for consumer items such as cordless telephones, as well as wireless business systems. It therefore is important that this impending problem be acknowledged and taken into account in proceedings related to PR Docket 93-61.

Finally, it should be noted that as Teletrac modifies and refines its designs, the parameters used in the calculations presented here may change, but the fundamental conclusions will not. One such change might be a modified pulse shape to give a waveform that provides better ranging performance than the BPSK waveform that the current generation of Teletrac's equipment apparently uses.[15] The use of a more efficient ranging waveform would increase the constant k_β, allowing more accurate TOA estimation with a given RF bandwidth. This

15. Because of the parabolic weighting function in (2), signal spectra that concentrate most of the power at the outer edges of the band will have larger values of β and give better TOA estimates, given the bandwidth constraint (this is discussed in [5], pp. 405-407).

would actually *reduce* the amount of bandwidth needed for a given level of performance. Another potential change is an increase in the direct sequence chip rate, which would result in an increase in the RF bandwidth, given a fixed k_β. This would affect the C/I threshold, but not the E_b/N_0 threshold. One reason for this would be to reduce the message duration, thereby increasing capacity. However, as already discussed, once the bandwidth is sufficiently higher to provide the required TOA estimation accuracy at end-of-range, increasing bandwidth further to reduce message duration does not seem to be a spectrum-efficient tradeoff.

These conclusions imply that (1) the 902-928 MHz band, with its high potential for uncontrolled interference, may not be the appropriate band for wideband pulse-ranging systems such as Teletrac's, and (2) that 8 MHz per system may not be necessary in any event. These two points in turn suggest that another band should be sought for those systems, and the spectrum requirement may not be as great as has been assumed.

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[2] ____, Comments, "In the Matter of Amendment of Part 90 of the Commission's Rules to Adopt Regulations for Automatic Vehicle Monitoring Systems," PR Docket No. 93-61, RM-8013, filed with the FCC June 29, 1993.

[3] ____, Reply Comments, "In the Matter of Amendment of Part 90 of the Commission's Rules to Adopt Regulations for Automatic Vehicle Monitoring Systems," PR Docket No. 93-61, RM-8013, filed with the FCC July 29, 1993.

[4] Federal Communications Commission, Notice of Proposed Rule Making, "In the Matter of Amendment of Part 90 of the Commission's Rules to Adopt Regulations for Automatic Vehicle Monitoring Systems," PR Docket No. 93-61, RM-8013, adopted March 11, 1993; released April 9, 1993.

[5] M. Skolnik, *Introduction to Radar Systems*, Second Edition, New York: McGraw-Hill, 1980.

[6] D. J. Torrieri, "Statistical theory of passive location systems," *IEEE Trans. Aerospace. Electron. Sys.*, vol. AES-20, pp. 183-198, March, 1984.

[7] Telecommunications Industry Association Mobile & Personal Communications Consumer Radio Section, Comments, "In the Matter of Amendment of Part 90 of the Commission's Rules to Adopt Regulations for Automatic Vehicle Monitoring Systems," PR Docket No. 93-61, RM-8013, filed with the FCC June 29, 1993.

[8] ____, Reply Comments, "In the Matter of Amendment of Part 90 of the Commission's Rules to Adopt Regulations for Automatic Vehicle Monitoring Systems," PR Docket No. 93-61, RM-8013, filed with the FCC July 29, 1993.

[9] Discussion with Yair Karmi (Vice President, Technology Development) and CZ Czerner (Vice President, Corporate Development) of PacTel Teletrac, during a meeting of the Telecommunications Industry Association Mobile & Personal Communications Consumer Radio Section, October 5, 1993, Washington, DC.

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[12] E. Green, "Radio link design for microcellular systems," *Br. Telecom Technol. J.*, vol. 8, pp. 85-96, Jan. 1990.

[13] E. Green and M. Hata, "Microcellular propagation measurement in an urban environment," *IEEE International Symposium on Personal, Indoor, and Mobile Radio Communications*, London, Sep. 1991, pp. 324-328.

[14] E. C. Jordan and K. G. Balmain, *Electromagnetic Waves and Radiating Systems*, Second ed., Englewood Cliffs, NJ: Prentice-Hall, 1968.

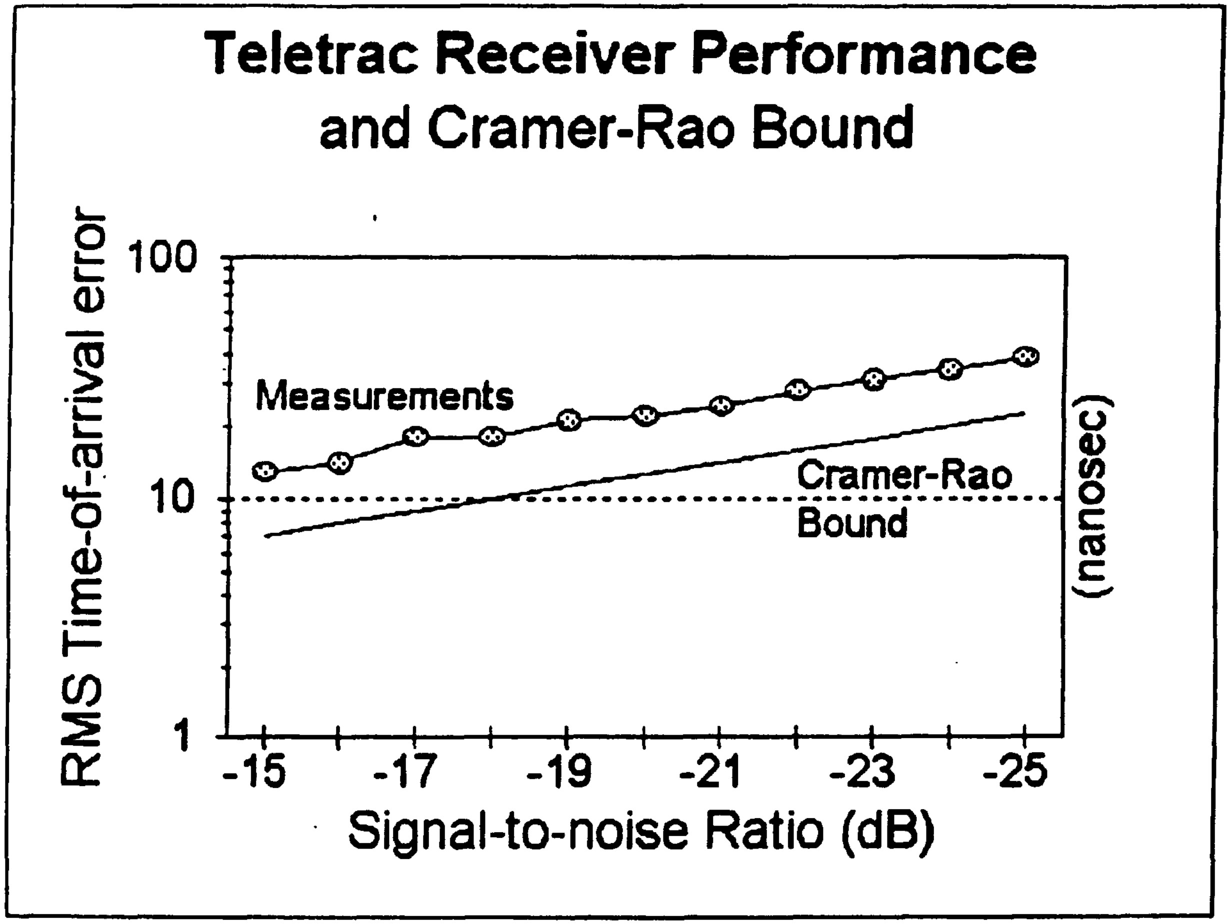


Figure 1

(reproduced from Appendix 2 of Teletrac's Comments, Fig. 12)

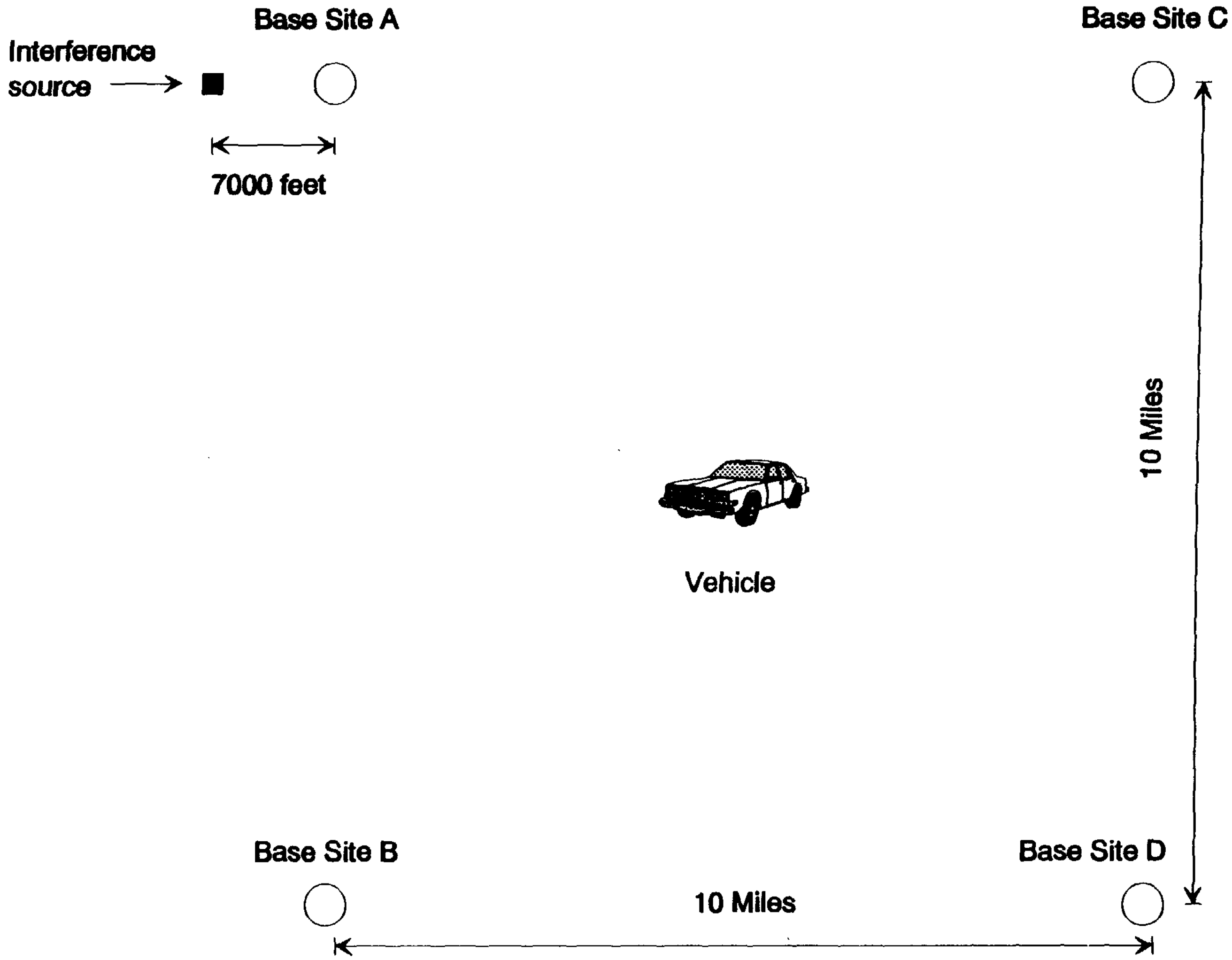


Figure 2 (Adapted from Appendix 2, Figure 4 of Teletrac's Petition)

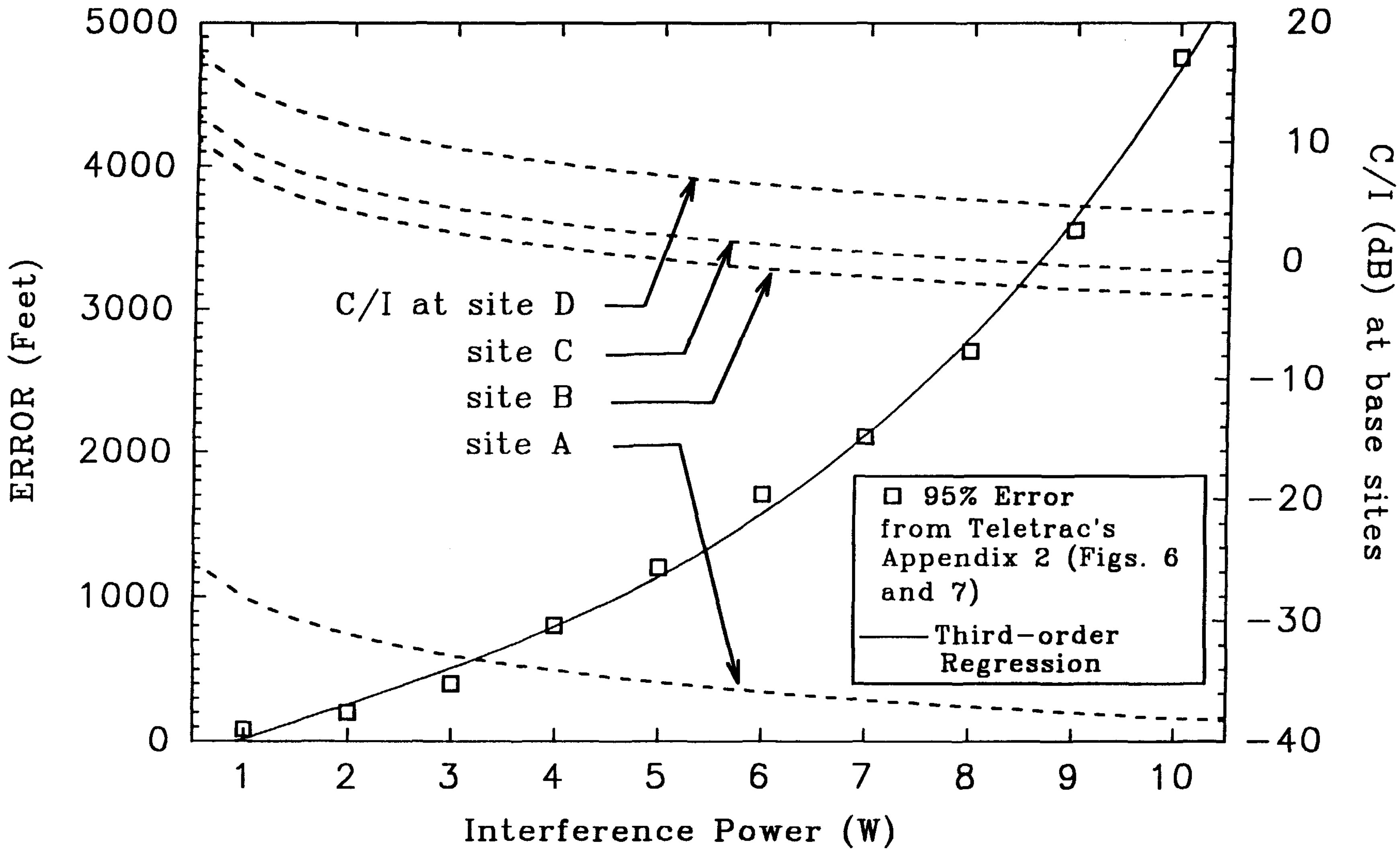

5000
4000
3000
2000
1000
0
ERROR (Feet)
20
10
0
−10
−20
−30
−40
C/I (dB) at base sites
1
2
3
4
5
6
7
8
9
10
Interference Power (W)
C/I at site D
site C
site B
site A
95% Error from Teletrac's Appendix 2 (Figs. 6 and 7)
Third−order Regression

Figure 3

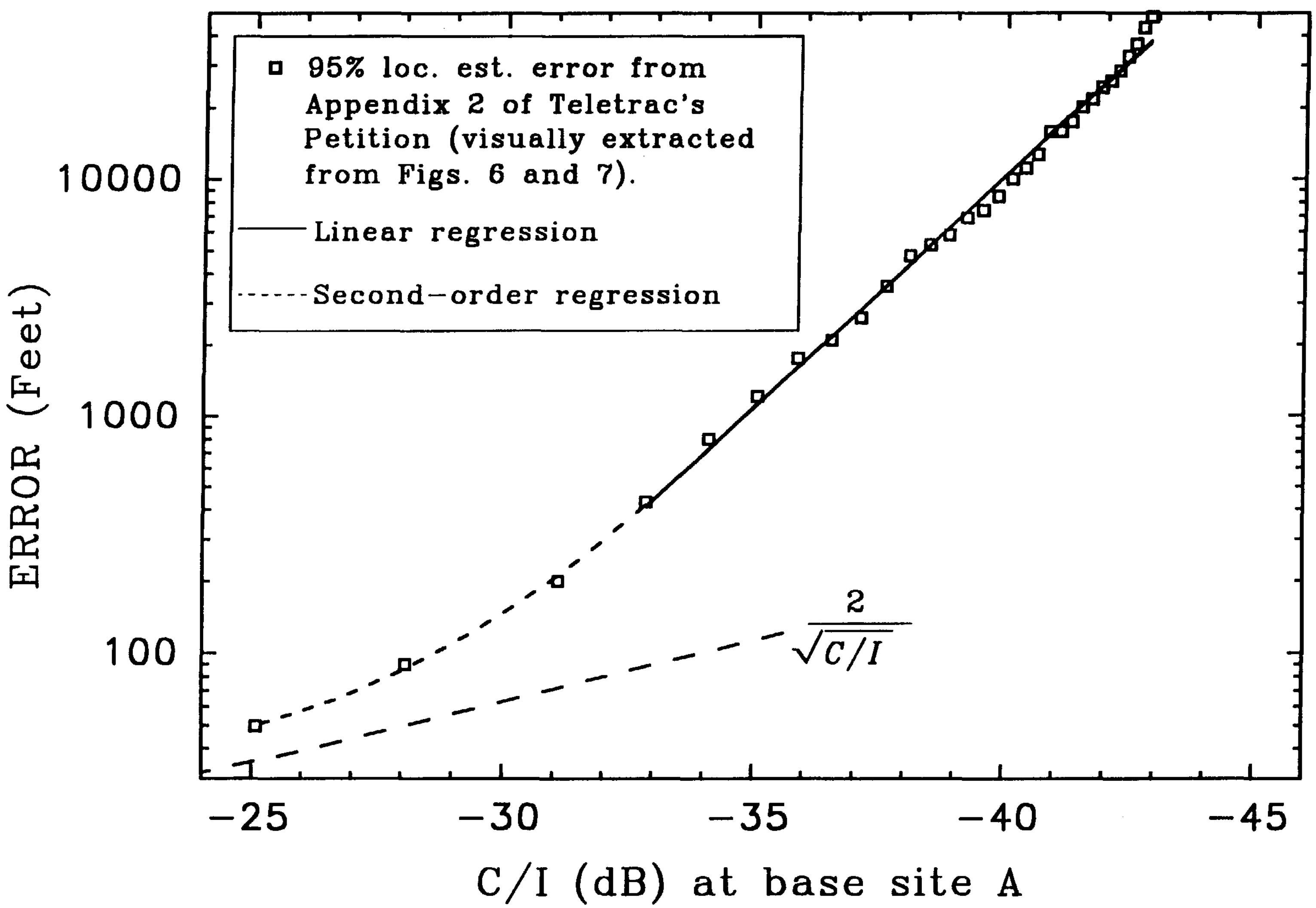
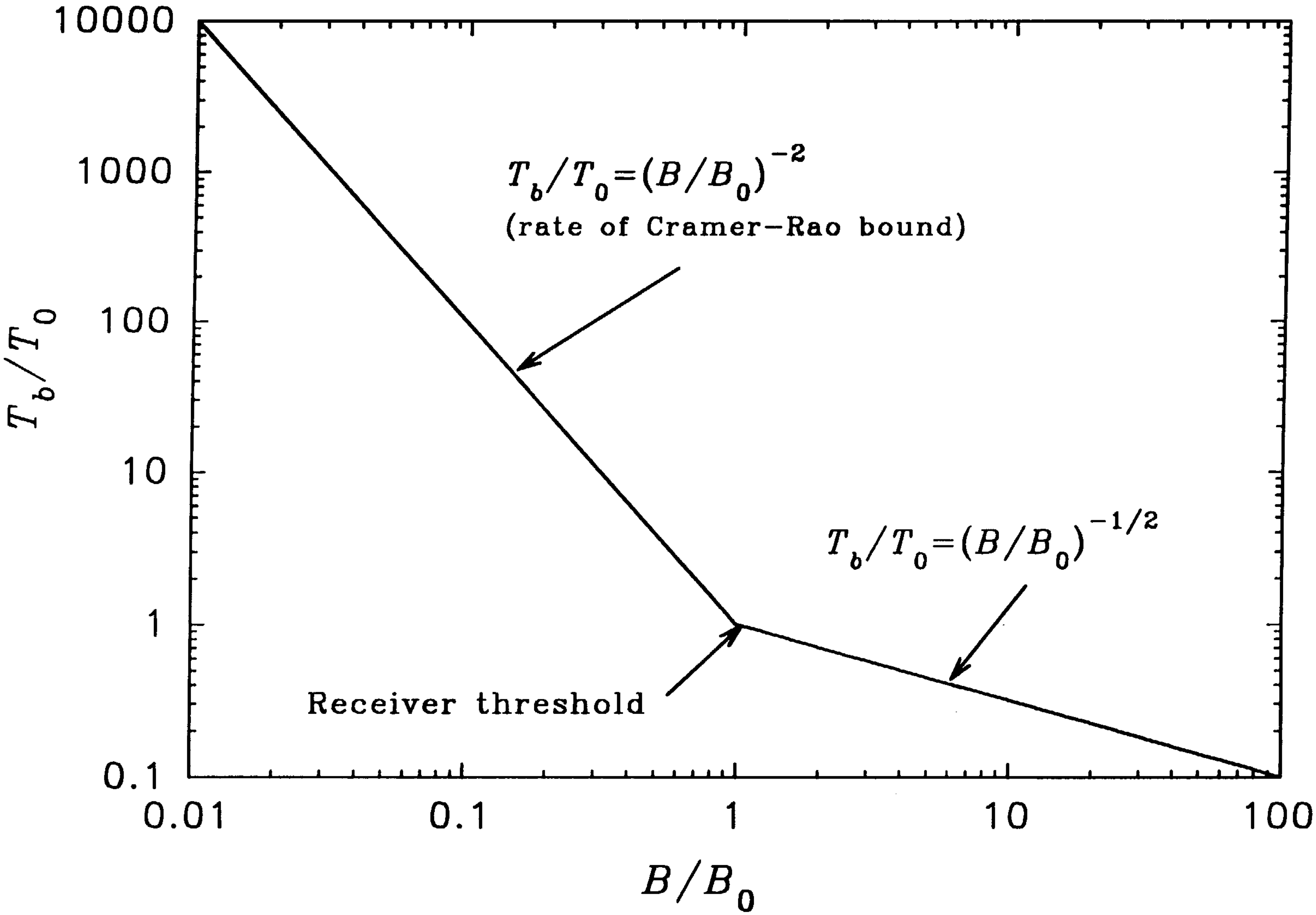
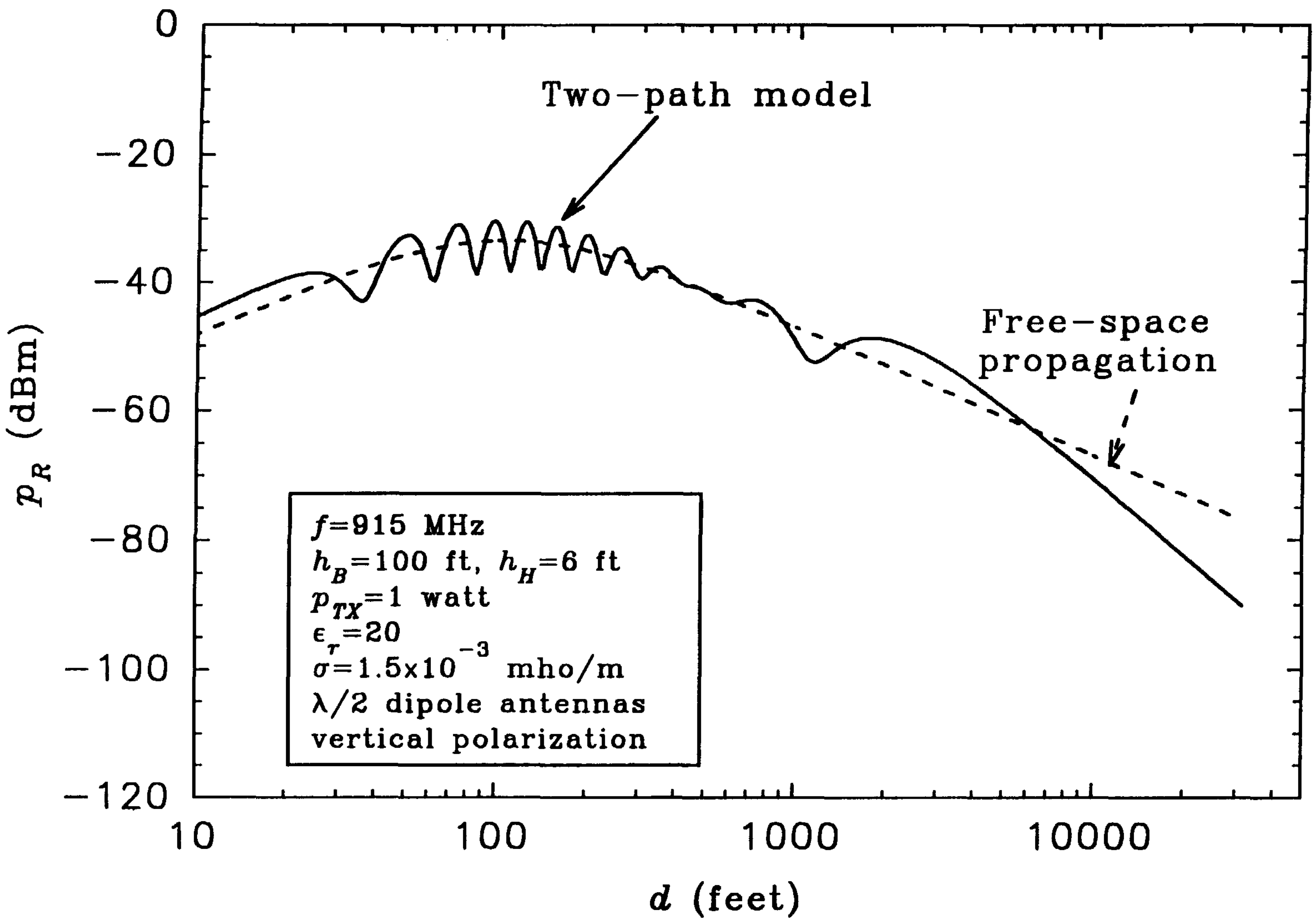

95% loc. est. error from Appendix 2 of Teletrac's Petition (visually extracted from Figs. 6 and 7).
Linear regression
Second-order regression
$\frac{2}{\sqrt{C/I}}$
10000
1000
100
ERROR (Feet)
−25
−30
−35
−40
−45
C/I (dB) at base site A

Figure 4



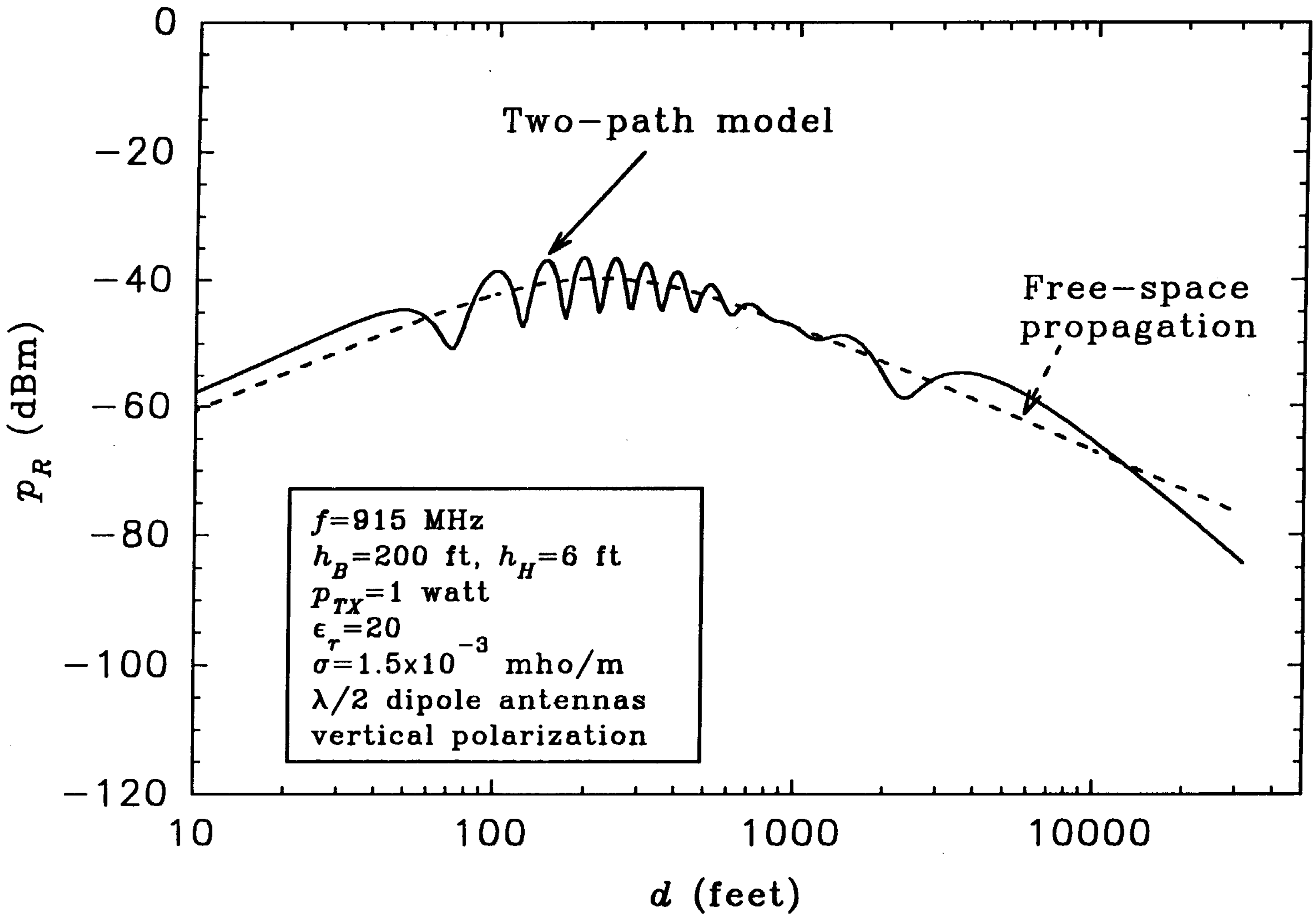
10000
1000
100
10
1
0.1
T_b/T_0
$T_b/T_0=(B/B_0)^{-2}$
(rate of Cramer–Rao bound)
$T_b/T_0=(B/B_0)^{-1/2}$
Receiver threshold
0.01
0.1
1
10
100
B/B_0

Figure 5



Two-path model
Free-space propagation
f=915 MHz
h_B=100 ft, h_H=6 ft
p_TX=1 watt
ε_r=20
σ=1.5x10^-3 mho/m
λ/2 dipole antennas
vertical polarization
p_R (dBm)
d (feet)
0
-20
-40
-60
-80
-100
-120
10
100
1000
10000

Figure 6



0
−20
−40
−60
−80
−100
−120
10
100
1000
10000
p_R (dBm)
d (feet)
Two−path model
Free−space propagation
f=915 MHz
h_B=200 ft, h_H=6 ft
p_{TX}=1 watt
ϵ_r=20
σ=1.5x10^{-3} mho/m
λ/2 dipole antennas
vertical polarization

Figure 7

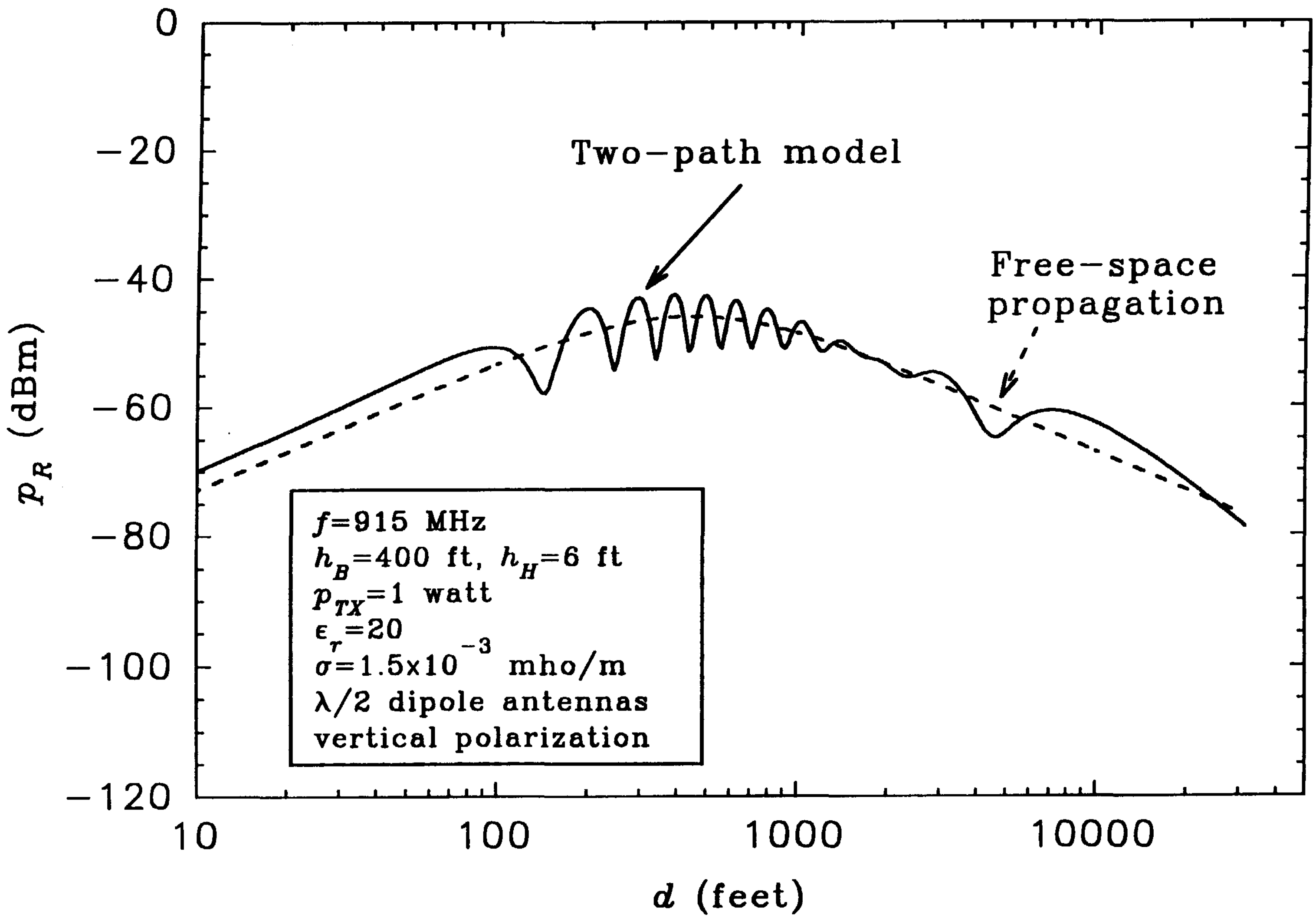
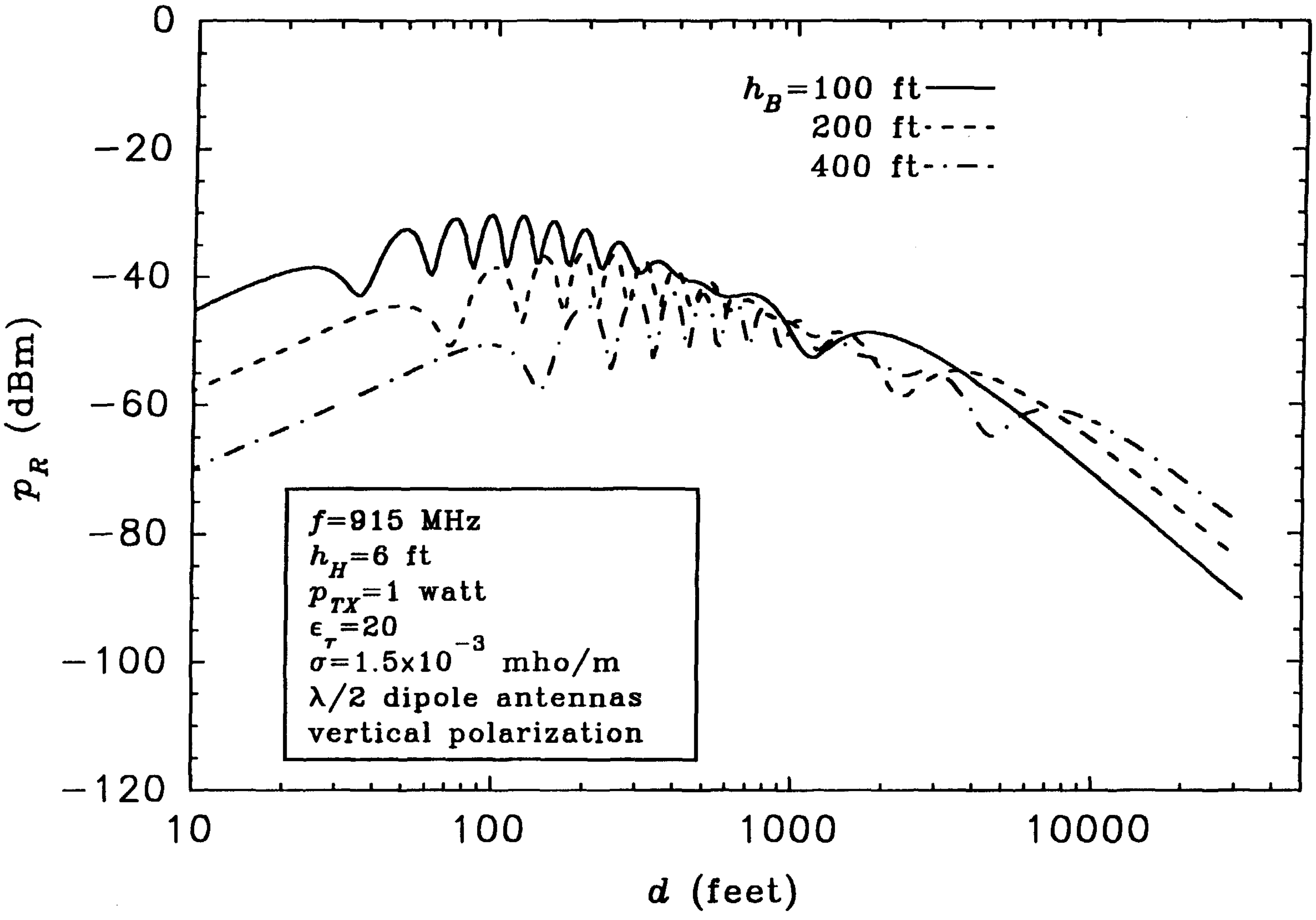

0
−20
−40
−60
−80
−100
−120
p_R (dBm)
10
100
1000
10000
d (feet)
Two−path model
Free−space propagation
f=915 MHz
h_B=400 ft, h_H=6 ft
p_{TX}=1 watt
ϵ_r=20
σ=1.5x10^{-3} mho/m
λ/2 dipole antennas
vertical polarization

Figure 8



0
−20
−40
−60
−80
−100
−120
10
100
1000
10000
p_R (dBm)
d (feet)
h_B=100 ft
200 ft
400 ft
f=915 MHz
h_H=6 ft
p_{TX}=1 watt
ϵ_r=20
σ=1.5x10^{-3} mho/m
λ/2 dipole antennas
vertical polarization

Figure 9

EXHIBIT B

NEWS RELEASE

TELECOMMUNICATIONS TIA INDUSTRY ASSOCIATION

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FOR IMMEDIATE RELEASE

TIA ANNOUNCES NEW IVHS SECTION

Washington, DC, March 2, 1994 -- The Telecommunications Industry Association (TIA) recently announced the formation of its new Intelligent Vehicle Highway System (IVHS) Section. This newly created Section of TIA will promote the use of communications technologies to accomplish IVHS system objectives.

IVHS is the application of advanced information processing, communications, sensors and control technologies designed to provide highly advanced management of traffic and offer a wide range of time-sensitive information to the traveler. IVHS is an emerging field that will improve safety, reduce congestion, enhance mobility, improve environmental quality and boost economic productivity.

"The IVHS Section will serve as an information conduit and clearinghouse for TIA-recommended positions on matters involving IVHS systems," said Dan Bart, TIA Vice President of Technical and Regulatory Affairs. The new IVHS Section of TIA will also develop U.S. positions as the Working Advisory Group to the International Standards Organization Technical Committee 204 - Working Group 16 on wide area communications.

Jim Nickel, Vice President-Engineering, Motorola Communications and Electronics, Inc., Schaumburg, Illinois, has been named Chairman of the new Section. "IVHS will create exciting new market opportunities for existing and emerging communications manufacturers, software and service providers," said Nickel.

-more-

IVHS AMERICA (IVHSA), a public/private venture serving as a federal advisory committee to the U.S. Department of Transportation, first approached TIA about setting communications standards for IVHS. Dan Toohey, Director of Standards and Telecommunications for IVHSA, said, "Communications, both wireless and wireline, will be the backbone of All IVHS systems. TIA's expertise and experience in this field will help us to accelerate IVHS deployments in the U.S. and internationally."

The next scheduled meeting of the new Section is April 13 at TIA headquarters in Washington, DC. Attendance and participation in the IVHS Section is open to members of TIA. Current members of TIA interested in Section membership should contact Jim Nickel at (708) 576-3443. Those companies interested in the Section, but not members of TIA, should contact Joe Grimes, TIA Director of Member Relations at (202) 457-5430. For Section activity information, contact Dan Bart, TIA Vice President of Technical and Regulatory Affairs at (202) 457-4936.

TIA is a full-service trade organization with membership of more than 550, including large and small companies, which provide telecommunications materials, products, systems, distribution services and professional services to the United States and countries around the world. TIA represents the telecommunications industry in association with the Electronic Industries Association.

PA Release 94-12
03.02.04

<u>CERTIFICATE OF SERVICE</u>

I, Stephaine Jones, do hereby certify that on this the 15th day of February, 1994, a copy of the foregoing Comments was served by first class United States mail, postage prepaid, to the following parties.

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